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Women's voice pitch lowers after pregnancy

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Abstract

Women's voice pitch (the perceptual correlate of fundamental frequency, $F0$) varies across the menstrual cycle and lowers after menopause, and may represent a putative signal of women's fertility and reproductive age. Yet, despite dramatic changes in women's sex hormone levels and bodies during and after pregnancy, previous between-subject and case studies have not found systematic changes in $F0$ due to pregnancy. Here, we tracked within-individual variation in 20 mothers' voices during their first pregnancy, as well as up to 5 years before conception and 5 years postpartum. Voice recordings from 20 age-matched nulliparous women were measured as a control. Linear Mixed Models indicated that $F0$ mean, range and variation changed significantly following pregnancy in mothers, controlling for age at time of recording, whereas we did not observe any $F0$ changes across corresponding timeframes in our sample of nulliparous controls. Mothers' voices became significantly lower-pitched and more monotonous during the first year postpartum compared to during pregnancy or before. These $F0$ parameters did not decrease within-individuals over a 5-year period prior to conception above and beyond the effects of ageing. Although voice pitch decreased following pregnancy, mothers' $F0$ parameters reverted after the first year postpartum, approaching pre-pregnancy levels. Our results demonstrate that pregnancy has a transient and perceptually salient masculinizing effect on women's voices.

Keywords: pregnant; fundamental frequency; sex hormones; vocal communication; nulliparous

Nonverbal properties of the human voice, particularly fundamental frequency (*F*0, perceived as voice pitch), correlate with a range of physical traits and behaviours, and predict individual differences in reproductive and social success (Pisanski & Bryant, 2018; Puts et al., 2016). Fundamental frequency is more sexually dimorphic in humans than in any other great ape (Puts et al., 2016). This sex difference emerges following a pubertal surge in the androgen levels of adolescent boys that masculinizes the larynx, lengthening and thickening the male vocal folds and resulting in a voice pitch that is around 75% lower in adult men than women (Titze, 1989). Fundamental frequency also varies considerably within the sexes; focusing mostly on men, numerous studies have linked individual differences in men's *F*0 to testosterone levels, facial masculinity, social dominance, and number of sex partners (Pisanski & Bryant, 2018 for review). There is therefore strong consensus that low *F*0 has been sexually selected in men to communicate threat potential and mate quality (Puts et al., 2016), and constitutes a secondary sex characteristic (Feinberg, 2008).

Women's voices, while comparatively less studied, also appear to communicate reproductive potential and fertility, and predict men's mate preferences. Men show preferences for indices of femininity and youth in women's traits, including high mean *F*0 in women's voices, presumably because these traits suggest a woman is of reproductive age and potentially fecund (Pisanski & Feinberg, 2018 for reviews; Puts, Jones, & DeBruine, 2012). Vocal attractiveness ratings are highest for women in their 20's and comparatively low for pre-pubertal and post-menopausal women (Röder, Fink, & Jones, 2013; Wheatley et al., 2014). Indeed, cross-sectional and longitudinal studies show that women's *F*0 either decreases gradually or stays relatively constant (barring cyclic fluctuations, see below) throughout their reproductive years, but consistently report a 10-35 Hz decrease in women's *F*0 following menopause (Abitbol et al., 1999; Amir & Biron-Shental, 2004). This drop in *F*0 may be caused by menopausal decreases in estrogens and increases in androgens resulting in swelling (edema) that alters the thickness and mass of the vocal folds (Derman, 1995; Hirano, Kurita, & Nakashima, 1983). Hormone therapies provide further evidence that testosterone permanently decreases women's *F*0 (Baker, 1999), whereas estrogen injections partially counter postmenopausal decreases in *F*0 (Lindholm, Vilkman, Raudaskoski, Suvanto-Luukkonen, & Kauppila, 1997). Taken together, there is good evidence that a women's voice pitch can indicate whether she is of reproductive age.

Studies have also shown intra-individual fluctuations in women's *F*0 across the menstrual cycle, suggesting that *F*0 may indicate cycle-to-cycle changes in fertility. Acoustic analyses reveal increases in women's *F*0 just prior to ovulation (Fischer et al., 2011) or at peak fertility (Bryant & Haselton, 2009), and playback studies show covariation between menstrual fluctuations in estrogen and progesterone levels and listeners' assessments of women's voice quality (Çelik et al., 2013). Although hormonal contraceptive usage, which stabilizes the cyclical variation in women's hormone levels, does not appear to predict differences in women's mean *F*0, lower levels of vocal perturbation among women taking monophasic birth control pills have been attributed to a stable hormonal balance leading to increased regularity in vocal fold vibration (Amir, Biron-Shental, & Shabtai, 2006).

Indeed, the vocal folds appear particularly sensitive to sex hormone levels which are known to fluctuate throughout the life cycle. Sex hormones may act on neuromotor control of the larynx (Higgins & Saxman, 1989) or act directly on the vocal fold mucosa that contain specific receptors for androgens, estrogens and progesterone (Newman, Butler, Hammond, & Gray, 2000).

Does pregnancy affect women's voice pitch?

Women's bodies change dramatically during and immediately following pregnancy. Estrogen, progesterone, testosterone and cortisol levels increase during pregnancy, followed by dramatic decreases following parturition (O'Leary, Boyne, Flett, Beilby, & James, 1991; Tan & Tan, 2013). Changes in anatomy and physiology during pregnancy include Reinke's edema (vocal fold swelling), decreased lung capacity, and altered respiration patterns (Speroff & Fritz, 2005; Tan & Tan, 2013). Many women also experience behavioural and psychological changes such as increased fatigue, changes in self-perception or self-presentation (e.g., perceived attractiveness and competency), and reduced mating motivation. These various endocrinological, physical and behavioural changes could affect women's *F*0 production during pregnancy and in the early years of childrearing.

Some singers and actresses have self-reported pregnancy-induced 'voice deepening' (e.g., Abramson et al., 1984). In turn, some voice clinicians have warned professional performers that pregnancy may alter their voices (Alford & Stasney, 2000; Brodnitz, 1971), sometimes encouraging them not to sing while pregnant (Sataloff, Emerich, & Hoover, 1997). Descriptions of laryngopathia gravidarum, an apparently permanent lowering of voice frequencies following pregnancy, emerged as early as the 1970's (Von Deuster, 1977). However, no empirical study has yet to show evidence of systematic and significant changes in women's *F*0 during or after pregnancy.

To our knowledge, six other studies have empirically tested for vocal changes during pregnancy (Cassiraga, Castellano, Abasolo, Abin, & Izbizky, 2012; Hamdan, Mahfoud, Sibai, & Seoud, 2009; Hancock & Gross, 2015; Lã & Sundberg, 2012; Saltürk et al., 2016; Von Deuster, 1977). Focusing predominantly on mean *F*0 and other spectral parameters, these studies have used between-subject designs or longitudinal case studies of a single individual. Hamdan et al. (2009) and Cassiraga et al. (2012) found no differences in mean *F*0 comparing pregnant women in their third trimester to non-pregnant controls. However, pregnant women's *F*0 increased by 8 Hz within 12 to 24 hours of giving birth (Hamdan et al., 2009). Saltürk et al. (2016) compared three groups of pregnant women, each in a different trimester of pregnancy, to a fourth group of non-pregnant controls and also found no significant group differences in mean *F*0. Finally, Hancock and Gross (2015) recorded one woman weekly during the last 30 weeks of her pregnancy and once at 21 weeks postpartum. The authors reported no systematic changes in mean *F*0 throughout pregnancy. None of these studies measured women's voices before becoming pregnant, and thus lacked a baseline for intra-individual comparison.

Several limitations may have contributed to the null results reported in these previous studies, and we designed our study to specifically address these issues. First, between-subject designs can introduce confounds due to demographic differences between pregnant and non-pregnant women, as well as individual differences in their baseline vocal parameters, whereas case studies entirely ignore between-individual variation. Second, no study has measured women's voices before conception. This makes it impossible to know from previous work whether *F*0 measured during or after pregnancy was different from women's pre-pregnant (i.e., baseline) levels. Third, in previous studies, voice measures were taken from scripted speech including vowel sounds and short read passages, rather than free speech that is naturally more variable. Finally, no study has examined the effect of pregnancy on *F*0 range (min and max) or variation, despite subjective reports on various websites and blogs from singers (e.g., C.S., 2008; Gerson, 2013) or voice coaches/therapists (e.g., Emerich, 2013; Gupta, 2018) of difficulty reaching high frequencies during or after pregnancy.

Present study

Here, we acoustically analysed archival recordings of 20 women experiencing their first pregnancy (Table S1a). We measured changes in *F*0 parameters before pregnancy (5 years), during pregnancy, and after pregnancy (5 years), and compared this to voice measures taken from 20 age-matched nulliparous controls (Table S1b) during corresponding timeframes. This allowed us to directly test whether mother's *F*0 decreased during or after pregnancy relative to pre-conception, and by how much, and whether and for how long these voice changes persisted postpartum. Although this study is the first longitudinal study of its nature, the small sample size (20 mothers, 20 controls) deems it exploratory.

For acoustic analysis, we extracted a total of 634 interview clips (277 min of audio) from mothers and controls (Table S2). Voice recordings of mothers were categorized into 5 phases: long-term pre-pregnancy, short-term pre-pregnancy, pregnancy, ST postpartum and LT postpartum (Figure 1), and those of controls were categorized into timeframes corresponding to the pregnancy, ST and LT postpartum phases in mothers. Multiple voice clips were collected for each woman during each phase (Table S2). We examined only mothers who were pregnant with their first child, analysed multiple long segments of natural free speech, and measured 5 voice pitch parameters: mean (*F*0 mean), minimum (*F*0 min), maximum (*F*0 max), standard deviation (*F*0 sd), and the coefficient of variation (*F*0 CV) using Praat software (Boersma & Weenink, 2016). See Methods and Tables S1-S2 for additional details.

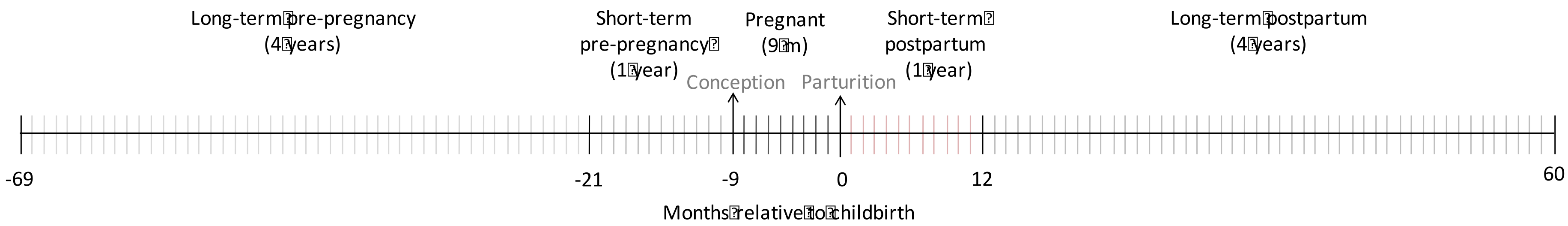

Figure 1. Timeline and categorization of voice recordings. Voice recordings were categorized into 5 pregnancy phases spanning approximately 10 years of each mother's life. Short-term (ST) pre-pregnancy and postpartum phases were one year prior to conception and one year after parturition, respectively, each approximating the duration of pregnancy. The long-term (LT) pre-pregnancy and postpartum phases each spanned a period of 4 years before and after the short-term phases, respectively. The long-term pre-pregnancy phase acted as a within-subject control phase to test whether *F*0 decreased within-individuals due to ageing prior to having ever conceived a child. The long-term postpartum phase acted as a recovery phase to test whether changes in *F*0 were transient or long lasting, and excluded clips during which some women were pregnant with a second child. As an additional control, data were collected from nulliparous controls during age-matched timeframes corresponding to the pregnancy and postpartum phases of mothers.

Results

Between-sample comparisons of *F*0

Linear Mixed Models (LMMs) fit by maximum-likelihood estimation, including participant identity as a subject variable with random intercept, sample (mothers, nulliparous controls) as a fixed factor, and woman's age at time of voice recording as a random covariate, showed no significant differences in any *F*0 parameters between mothers and controls collapsing across phases (all $F<1.3$, all $p>.271$). This result confirmed that the two samples of age-matched women could effectually be compared.

Within-individual changes in *F*0

Linear Mixed Models were then used to test for within-individual changes in each *F*0 parameter across pregnancy phases in mothers and across corresponding timeframes in controls. Each model included participant identity as a subject variable with random intercept and phase/timeframe as a fixed factor. To control for the potential effect of ageing on *F*0, women's age at time of voice recording was included as a random covariate. Mother's age at parturition (childbirth), included as a fixed covariate, showed no effect (all $F<2.9$, all $P>.103$), and the corresponding age of nulliparous controls also showed no effect (all $F<1.03$, $P>.323$), and was therefore excluded from final models. Significant effects were further examined using pairwise tests with Šidák correction for multiple comparisons. In our sample of mothers, residuals were computed for each *F*0 parameter controlling for participant identity (random intercept) and mother's age at voice recording (fixed covariate). This allowed us to plot within-individual changes in *F*0 across pregnancy phases above and beyond what could be attributed to ageing.

Mothers

The results of LMMs confirmed that all $F0$ parameters changed significantly as a function of pregnancy phase among mothers, controlling for the mother's identity and age at the time of voice recording (Table 1a).

Table 1. Linear Mixed Models examining $F0$ changes as a function of (a) pregnancy phase in mothers, and (b) corresponding timeframe in nulliparous controls.

Voice parameter	**Model source**	df_1, df_2	F	p
(a) Mothers (n=20)				
$F0$ mean	Intercept	1, 20.0	2562.25	<.001
	Pregnancy phase	4, 367.1	11.5	<.001***
$F0$ min	Intercept	1, 18.1	1380.5	<.001
	Pregnancy phase	4, 394.8	3.2	.014*
$F0$ max	Intercept	1, 20.2	1471.3	<.001
	Pregnancy phase	4, 393.5	9.7	<.001***
$F0$ sd	Intercept	1, 20.3	588.8	<.001
	Pregnancy phase	4, 392.1	7.9	<.001***
$F0$ CV	Intercept	1, 20.4	1096.4	<.001
	Pregnancy phase	4, 393.7	3.8	.005**
(b) Nulliparous controls (n=20)				
$F0$ mean	Intercept	1, 23.0	2054.3	<.001
	Corresp. timeframe	2, 210.6	0.7	.52
$F0$ min	Intercept	1, 26.4	925.5	<.001
	Corresp. timeframe	2, 213.4	0.4	.679
$F0$ max	Intercept	1, 24.0	1108.5	<.001
	Corresp. timeframe	2, 211.4	1.7	.186
$F0$ sd	Intercept	1, 23.6	453.4	<.001
	Corresp. timeframe	2, 211.0	2.8	.064
$F0$ CV	Intercept	1, 24.2	722.7	<.001
	Corresp. timeframe	2, 211.6	2.8	.060

LMM controlling for women's identity and age at time of voice recording. Effect of pregnancy phase significant at: *** p<.001; ** p<.01; * p<.05

Planned pairwise comparisons among pregnancy phases with Šidák correction are shown in Figure 2a (see Table S3a for full pairwise comparison matrix with/without adjusting for multiple comparisons). Among mothers, we observed a decrease in all *F*0 parameters one year postpartum compared to one year pre-pregnancy (Fig. 2a: ST Post vs ST Pre). Thus, in the year following the birth of their first child, women's *F*0 parameters dropped on average by 14.6 Hz (*F*0 mean), 13.6 Hz (*F*0 min), a sizeable 43.7 Hz (*F*0 max), 8 Hz (*F*0 sd), and .022 Hz (*F*0 CV) compared to the year prior to conception. Women's *F*0 mean, max, sd and CV values were also lower one year postpartum compared to during pregnancy (Fig. 2a: ST Post vs Pregnant). This indicates that women's voices became relatively lower-pitched and more monotonous after giving birth than during pregnancy or before.

Pairwise comparisons further confirmed no significant differences in any *F*0 parameter between the long-term (i.e., control phase) and short-term pre-pregnancy phase (Fig. 2a: LT Pre vs ST Pre), indicating that *F*0 did not decrease within-individuals over a 5-year period prior to conception above and beyond the effects of ageing. Finally, a clear pattern was observed in which mother's *F*0 parameters increased or 'reverted' in the long-term postpartum phase, approaching pre-pregnancy levels. After adjusting for multiple comparisons (Table S3a), mother's mean *F*0 in the long-term postpartum phase was not statistically different than in the year prior to pregnancy (Fig. 2a: LT Post vs ST Pre), and their *F*0 min, max, sd, and CV were not statistically different than in the 5 years prior to pregnancy (Fig. 2a: LT Post vs LT/ST Pre). This indicates that mother's voices, although lower-pitched and more monotonous in the year following pregnancy, increased again to (age adjusted) pre-pregnancy levels in the four years following that. Residuals for each *F*0 parameter, showing changes in *F*0 by phase above and beyond the effects of ageing, are plotted in the bottom panel of Figure 2a.

Nulliparous controls

For childless women, the results of LMMs controlling for women's identity and age at the time of voice recording showed no significant changes in any *F*0 parameter across timeframes (Table 1b). Thus, in contrast to mothers, the voice pitch of age-matched nulliparous controls remained relatively stable across an average period of 7.5 years, corresponding to the pregnancy and postpartum phases in mothers (Figure 2c). Although temporal changes in nulliparous women's *F*0 sd and CV approached significance (Table 1b), no pairwise comparisons reached statistical significance following Šidák correction (all P>.08) and the observed trends were in the opposite direction as those found in mothers (i.e., *F*0 sd and CV showed a nonsignificant trend toward increasing over time in nulliparous controls; see Table S3b for full pairwise comparisons matrix).

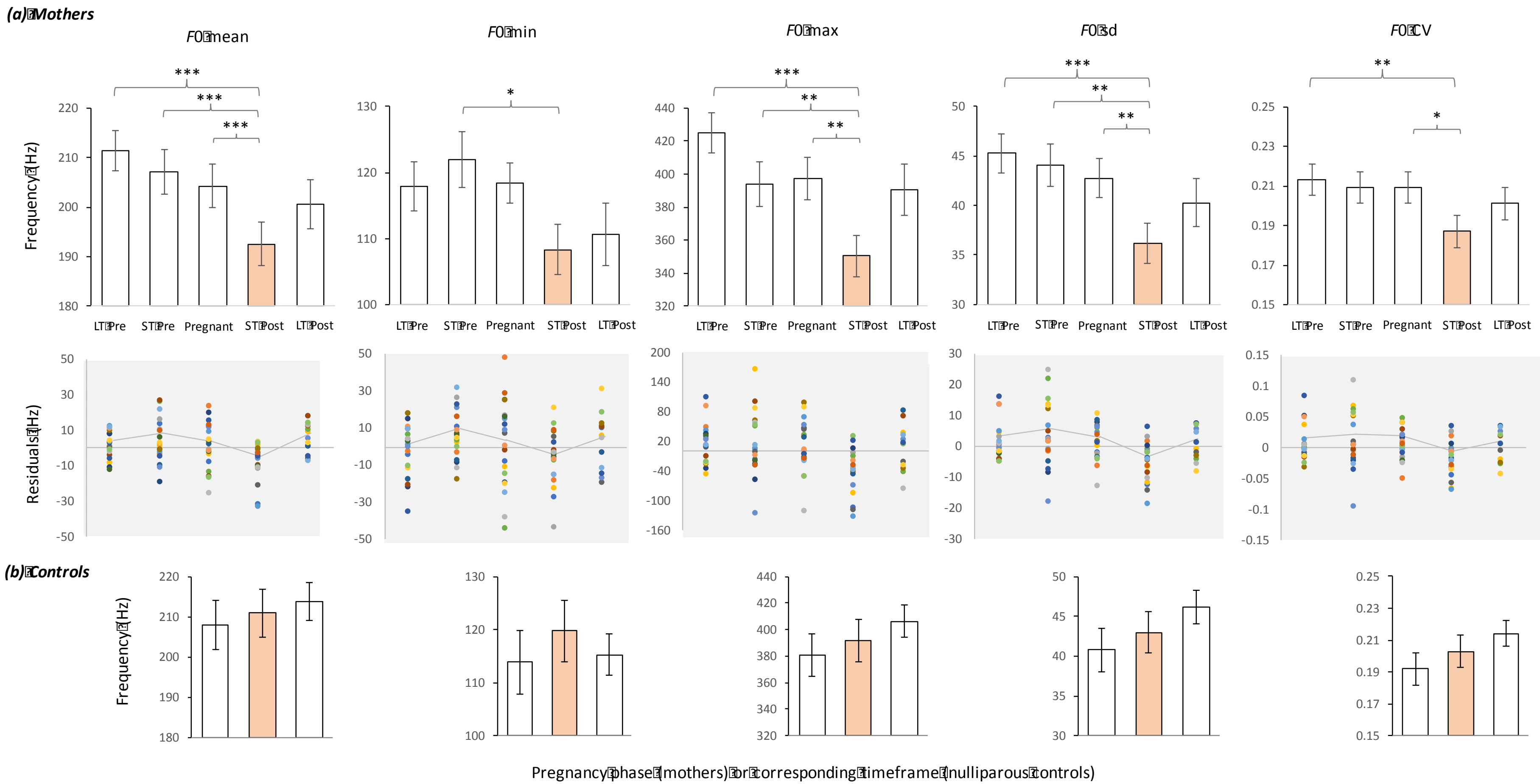

Figure 2. Pregnancy-related changes in mother's voice pitch and a lack of corresponding changes in the voice pitch of nulliparous controls. Estimated marginal means of fundamental frequency (*F*0) parameters across pregnancy phases in mothers (panel a) and across age-matched timeframes in nulliparous controls corresponding to the pregnancy, ST and LT postpartum phases of mothers (panel b). Shaded bars represent one year postpartum (or corresp. timeframe), in which changes were observed in the *F*0 of mothers, but not controls. Error bars represent the standard error of the mean (SEM), and significant differences among phases/timeframes are shown for planned

comparisons following Šidák correction, where * p<.05, **p<.01, ***p<.001. Residual values for $F0$ parameters showing within-individual changes in mother's $F0$ across pregnancy phases, above and beyond changes attributed to ageing, are shown at the bottom of panel a. Each mother's residuals are plotted separately for each phase, and a grey line is drawn connecting phase means. LT Pre = long-term pre-pregnancy (4 years); ST Pre = short-term pre-pregnancy (1 year); Pregnancy (9 months); ST Post = short-term postpartum (1 year); LT Post = long-term postpartum (4 years).

Discussion

The results of this longitudinal study show that women's average voice pitch, pitch range and pitch variability decrease after giving birth to their first child. These voice changes endure for at least one year postpartum, later returning to near pre-pregnancy levels controlling for ageing. Previous studies have focused on voice changes during pregnancy (Cassiraga et al., 2012; Hamdan et al., 2009; Hancock & Gross, 2015; Lã & Sundberg, 2012; Saltürk et al., 2016; Von Deuster, 1977). Here, we show that although women's voice pitch shows a trend toward lower values during pregnancy, significant decreases in pitch occur after pregnancy, and are transient. We did not observe any $F0$ changes across corresponding timeframes in our sample of age- and profession-matched nulliparous controls, offering further support that the postpartum $F0$ changes we observed in mothers cannot be attributed to age-related $F0$ variation, or to the women's line of work.

There are several possible, non-mutually exclusive mechanisms that may help to explain why women's voices are temporarily masculinized following pregnancy. Although respiration patterns and lung capacity change during pregnancy (Gilroy, Mangura, & Lavietes, 1988; Tan & Tan, 2013), this is unlikely to explain postpartum voice changes in the year after pregnancy, as lung volume returns to normal within two days of parturition (Gilroy et al., 1988). However, in the months after giving birth, women's estrogen, progesterone, and cortisol levels decrease dramatically compared to pregnancy levels. In addition to potentially inducing postpartum depression in some women (Hendrick, Altshuler, & Suri, 1998; Mehta et al., 2014), abrupt drops in sex steroid levels may affect $F0$ by acting directly on hormone receptors on the vocal folds or indirectly on neural laryngeal control (Higgins & Saxman, 1989; Newman et al., 2000).

Postpartum decreases in *F*0 may also be a product of behavioural changes. Women experience increased mental and physical fatigue during the first year of childrearing, as well as changes in mood. Although robust evidence that fatigue decreases women's *F*0 is lacking (Cho, Yin, Park, & Park, 2011), voice pitch plays a key role in the communication of emotion and affect (Sauter, Eisner, Calder, & Scott, 2010). Alternatively, women may behaviorally modulate their voices. There is growing evidence that women and men speak with a lower *F*0 in specific social contexts, particularly when experiencing (or wishing to portray) a high degree of competence and authority (Pisanski, Cartei, McGettigan, Raine, & Reby, 2016). New mothers may also experience decreased motivation to volitionally raise their voice pitch. Although a high voice pitch in women can signal youth and femininity to potential mates, it is likewise associated with perceptions of immaturity and submissiveness (Pisanski & Bryant, 2018 for review).

The magnitude of voice pitch changes observed in our sample of women was large. Women's mean and minimum *F*0 dropped by approximately 14 Hz (approx. 1.3 semitones) after giving birth relative to pre-conception levels. Women's maximum *F*0 dropped by 44 Hz (approx. 2.2 semitones), indicating that reaching high frequencies may be particularly inhibited in the year following pregnancy. Such voice changes are likely to be easily perceptible as they are well beyond the just-noticeable differences in voice pitch perception (Pisanski & Rendall, 2011; Re, O'Connor, Bennett, & Feinberg, 2012). However, playback studies are now needed to test whether listeners can discriminate mother's voices recorded in pre-pregnancy, pregnancy and postpartum phases, or can differentiate mothers from non-mothers from the voice alone. In addition, while the effects of a relatively low-pitched and monotonous (i.e., masculine) voice on listeners' biosocial judgments are well documented (Pisanski & Bryant, 2018 for review), playback studies are also needed to assess whether postpartum decreases in voice pitch influence listeners' voice-based judgments of new mothers.

The aim of this study was to test whether women's voice pitch changes during or after pregnancy relative to before conception, and to what extent, employing methods that address many of the shortcomings of previous investigations (i.e., we use a longitudinal design; include a 'pre-pregnancy' baseline phase; utilize natural rather than scripted speech; and measure multiple pitch parameters). The use of archival recordings allowed us to readily explore this research question by analyzing within-individual changes in women's voice pitch over a span of 10 years. This would be difficult with real-time voice recording, particularly recording women's voices before conception. However, in future work, voice recordings collected as part of a planned longitudinal study will have the benefit of allowing researchers to also systematically measure and control for other variables to examine covariation in $F0$, sex hormone levels, and behavioral measures to better understand the mechanisms driving postpartum voice changes. More generally, longitudinal measures of hormone levels and vocal parameters across the lifetime could reveal whether large hormonal shifts predict large changes in pitch. Researchers may also test whether women who adopt children or acquire a child through surrogacy show decreases in $F0$ parameters. If so, this could suggest that the mechanism is at least partially behavioral. Questionnaire data could help reveal whether greater subjective experience of fatigue, mood changes or postpartum depression predicts larger decreases in voice pitch in the year after parturition. Finally, future work may examine whether women's $F0$ parameters also drop following the birth of subsequent children, and whether these voice changes are amplified following a multiple birth (e.g., twins).

Our sample of mothers and nulliparous controls included actresses, journalists or reporters, celebrities, and singers. Although these women are performers or public figures by profession, all voice recordings used in this study (from both mothers and controls) were taken from unscripted interviews in which the women were not explicitly acting. Moreover, while it is possible that the voice changes we observed were partially behavioural (i.e., voice modulation), we did not observe analogous voice changes in nulliparous controls whose professions matched those of the mothers, suggesting that profession cannot itself explain our pattern of results. Nevertheless, we cannot rule out an interaction between profession and pregnancy phase. Future longitudinal work utilizing a larger sample of women in a wider range of professions, and cultures, is now clearly needed to establish the replicability and generalisability of our results.

Although our data cannot offer an answer to the question of whether postpartum voice changes represent an evolved signal or a byproduct, this is an important question worth considering here, and testing in future work, particularly given the known influence of voice pitch on social and reproductive success, and its potential role in communicating female fertility and fecundity (e.g., ovulation and menopause: Abitbol, Abitbol, & Abitbol, 1999; Amir & Biron-Shental, 2004; Bryant & Haselton, 2009; Çelik et al., 2013; Fischer et al., 2011). While it is possible that selection could operate on women to honestly communicate, or deceptively exaggerate or suppress, postpartum state, or on men to reliably detect the reproductive states of women (see e.g., Haselton & Gildersleeve, 2011), the most parsimonious explanation for our results is that postpartum changes in women’s voices reflect a byproduct of physiological, anatomical and/or behavioural changes following pregnancy. To test these competing hypotheses, additional research is needed to identify the mechanisms driving postpartum voice changes, as described above, and their potential influence on listeners.

Methods

Subjects

We analysed voice recordings collected from 40 adult women, including 20 women who had given birth to their first child, and 20 nulliparous controls who had never given birth. We first searched online for female public figures (actresses, journalists, reporters, singers and celebrities) who had given birth to their first child no less than four years ago. This search produced a list of twenty-nine women. We then excluded women (*n*=9) for whom we could not find 10 years' worth of frequent (i.e., at least bi-monthly), standardized, high-quality voice recordings spanning several years before and after their first pregnancy. Our final sample of mothers included 20 women, who were born between the years 1966 and 1987 and were between 27 and 41 years of age (mean 35.3) when their first child was born (Table S1a). As voice recordings were collected up to 5 years before and after childbirth, mother's ages at time of voice recording ranged from 22.6 to 49.7. Their occupations included actress/celebrity (*n*=9), journalist/reporter (*n*=8), and singer/performer (*n*=3).

Nulliparous controls were located online by searching for women, with the same professions as our mothers, who had never had a child and for whom we could locate several years of high-quality voice recordings. To match our sample size of mothers, we terminated our search once we had obtained data from 20 nulliparous controls. These women were born between 1958 and 1980, and were thus age-matched to our sample of mothers at parturition (mean age 36.08), such that the age of each nulliparous control matched the age of one given mother at parturition by an average of ± 10.7 months (min 1.2 months, max 34.8 months; Table S1b). The occupations of nulliparous controls were matched to those of mothers and included actress/celebrity (*n*=13), journalist/reporter (*n*=6), and singer/performer (*n*=1). See Table S1for subject-level demographic data.

Although no previous study has examined long-term effects of pregnancy on the voice, studies examining longitudinal changes in women's *F*0 more generally (e.g., de Pinto & Hollien, 1982; Russell, Penny, & Pemberton, 1995) indicated that 20 women (per group) is a sufficient sample size to detect long-term *F*0 changes where they are present in either mothers or controls.

Voice recordings

Voice recordings were extracted from interviews made available through the UCLA Digital Civic Learning Search Engine (a large collection of archived digital media from a range of television networks dating 2005-present) and from footage publically available online (e.g., YouTube). We searched for interviews that took place within the allotted timeframe by inputting each woman's name, the word "interview", and the dates of interest into Google Videos or UCLA search engines. Interview dates were then verified through the UCLA database and via cross-sourcing with online databases (e.g., television guides; Internet Movie Database). Inclusion criteria for interview clips were a lack of strong emotional content, shouting, and background noise. We searched for and randomly selected 4 clips per phase/timeframe for each woman that met these criteria, attaining an average of 4.4 ± 2.2 interviews per phase for each mother (Table S2a) and 3.8 ± 2.7 interviews per corresponding timeframe for each nulliparous control (Table S2b). A total of 634 clips were extracted for analysis with an average duration of 29 ± 16.5 s (mothers) and 21.3 ± 13.5 s (controls), totalling 277 minutes of audio (see Table S2 for clip descriptives by woman and phase/timeframe).

For mothers, voice recordings were categorized into five phases spanning approximately 10 years of each mother's life: long-term (LT) pre-pregnancy (102 clips, 57.1 min in total), short-term (ST) pre-pregnancy (69 clips, 25. 1 min), pregnancy (87 clips, 38.7

min), ST postpartum (99 clips, 44.9 min) and LT postpartum (50 clips, 31 min; see Fig. 1). Birthdates of all children were determined and cross-checked using online sources, and dates of conception were estimated using a conservative threshold of 284 days maximum length of gestation (Jukic, Baird, Weinberg, McConnaughey, & Wilcox, 2013). Fourteen mothers conceived a second child within five years of giving birth to their first child (mean number of days between pregnancies: 636, range 157 to 1756). Clips collected in postpartum phases excluded those in which these women were pregnant with a subsequent child. For nulliparous controls, voice recordings were categorized into three timeframes which corresponded to the phases of pregnancy (40 clips, 15.1 min), ST postpartum (45 clips, 17.5 min) and LT postpartum (142 clips, 48 min) experienced by our sample of mothers. Together, these timeframes spanned approximately 7.5 years of each nulliparous woman's life.

Acoustic analysis

Audio was extracted from each clip and saved as WAV files using Boom 2 and Praat v 6.0.19 software (Boersma & Weenink, 2016) (mono, 48 kHz sampling frequency). Segments of multi-voicing, acute noise, and nonverbal vocalizations (e.g., laughter) were manually removed in Praat. We measured 5 parameters of fundamental frequency: mean ($F0$ mean), minimum ($F0$ min), maximum, ($F0$ max), standard deviation ($F0$ sd), and the coefficient of variation ($F0$ CV) using Praat's autocorrelation algorithm with a search range of 60-600 Hz and a time step of 0.01 s. Whereas $F0$ mean represents average voice pitch, and $F0$ min and max represent its range, $F0$ sd and CV represent pitch variability. A less variable, more monotonous voice will have lower values of $F0$ sd. However, because $F0$ sd decreases as $F0$ mean increases, we additionally measured $F0$ CV that represents pitch variability corrected for mean ($F0$ sd/$F0$ mean). Erroneous pitch values and spurious octave jumps were manually corrected by selecting the appropriate $F0$ in Praat's pitch object window (Raine, Pisanski, & Reby, 2017; Reby, Levréro, Gustafsson, & Mathevon, 2016). Acoustic measures were performed on the entire duration of each clip. Silences were not removed before analysis as Praat's autocorrelation algorithm does not track $F0$ in silent segments of speech.

Ethics

The study was reviewed and approved by the Sciences and Technology Cross-Schools Research Ethics Committee (C-REC) of the University of Sussex (ER-REBY-2,8). The audio samples used for acoustic analysis were extracted from publicly or institutionally available video files.

Data availability

The dataset supporting this article is openly available on the Sussex Research Online (SRO) repository (http://sro.sussex.ac.uk/id/eprint/74811).

Authors' contributions

K.P. and D.R. designed the investigation. K.P. and K.B. collected the data and performed acoustic analysis. K.P. and D.R. conducted statistical analysis. K.P. drafted the manuscript and created all figures. The manuscript was reviewed, edited and approved by all authors, who agree to be accountable for the work.

Competing interests

The authors report no competing interests.

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